Measurement of the polarization vector of the e^+ from the decay of polarized μ^+ and its implications on

- G_F (Fermi coupling constant)
- TRI (time reversal invariance)
- PBSM (physics beyond the standard model)

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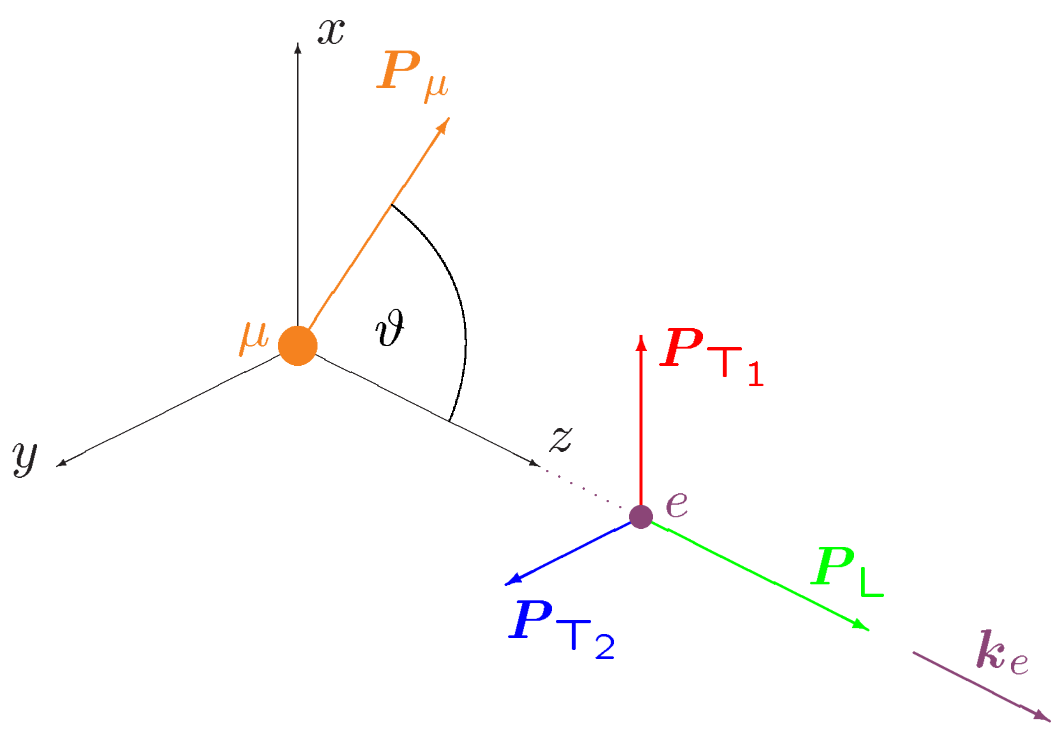
2. Observables



$$P_{\mathsf{T}_1} = f_1(E, \vartheta, \eta, \eta'')$$

$$P_{\mathsf{T}_2} = f_2(E, \vartheta, \tfrac{\alpha}{A}, \tfrac{\beta}{A})$$

The standard model predicts:

$$\langle P_{\mathsf{T}_1}(\vartheta = 90^\circ)\rangle_E = -1.6 \times 10^{-3}$$

$$P_{\mathsf{T}_2} \equiv 0$$

A nonzero P_{T_2} would signal violation of time reversal invariance. This is the only purely leptonic reaction for which TRI has been tested up to now.

3. Matrix Element

$$\mathcal{M} = \frac{4G_\mathrm{F}}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \varepsilon,\mu=R,L}} g^\gamma_{\varepsilon\mu} \langle \overline{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle \overline{\nu}_m | \Gamma_\gamma | (\mu)_\mu \rangle$$

The index γ labels the type of interaction:

Γ^S	=	4-scalar
Γ^V	=	4-vector
Γ^T	=	4-tensor

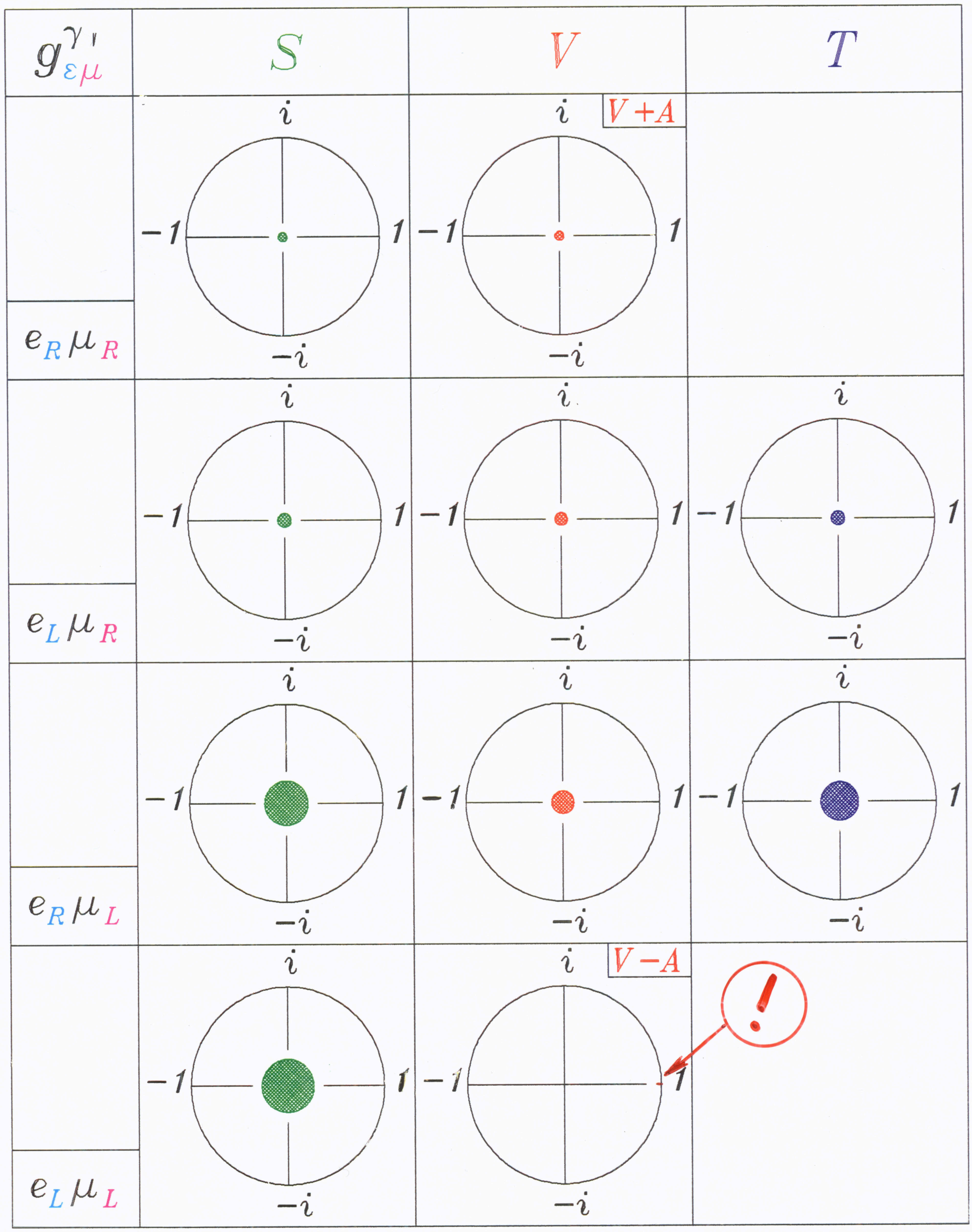
The indices ε, μ indicate the chiralities of the spinors of the observed (charged) leptons. The chiralities n, m of the neutrinos are uniquely determined for given γ, ε and μ.
The transverse polarization component P_{T_1} yields the low energy parameter η *without* the suppression factor m_e/m_μ of η in the energy spectrum of the decay positron. These interference terms allow for sizeable effects.

$$\eta = \frac{1}{2} Re \{ g^V_{LL} g^{S*}_{RR} + g^V_{RR} g^{S*}_{LL} + g^V_{LR} (g^{S*}_{RL} + g^{T*}_{RL}) + g^V_{RL} (g^{S*}_{LR} + g^{T*}_{LR}) \}$$

In the standard model

$$g^V_{LL} = 1$$

$$g^\gamma_{\varepsilon\mu} = 0 \quad \text{(all other interactions)}$$

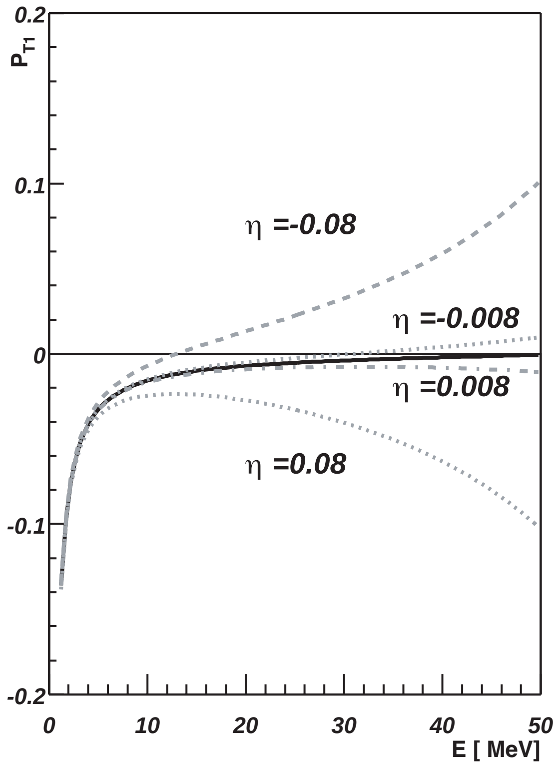


$g^{\gamma'}_{\varepsilon\mu}$
S
V
T
$e_R \mu_R$
$e_L \mu_R$
$e_R \mu_L$
$e_L \mu_L$
V+A
V−A
i
−1
1
−i
!

Assuming 1 additional interaction and knowing that

$$g^V_{LL} \approx 1,$$

one deduces:



$$P_{T_1}(E_e) \to \eta \approx \frac{1}{2} Re\{g^S_{RR}\}$$

$$P_{T_2}(E_e) \to \frac{\beta'}{A} \approx \frac{1}{4} Im\{g^S_{RR}\}$$

Main scientific interests:

P_{T_1}: Precise determination of Fermi coupling constant G_F

P_{T_2}: Test of time reversal invariance

4. Fermi coupling constant

Should be independent of masses and radiative corrections:

Universal coupling constant

$$G_F^2 = \quad 192\pi^3 \cdot \frac{\hbar}{\tau_\mu} \cdot \frac{1}{m_\mu^5} \cdot$$

$$\left\{1 + \frac{\alpha}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right\} \cdot \left\{1 - \frac{3}{5}\left(\frac{m_\mu}{m_W}\right)^2\right\} \cdot$$

$$\left\{1 - 4\eta \cdot \frac{m_e}{m_\mu} - 4\lambda \cdot \frac{m_{\nu_\mu}}{m_\mu}\right.$$

$$\left. +8\left(\frac{m_e}{m_\mu}\right)^2 + 8\left(\frac{m_{\nu_\mu}}{m_\mu}\right)^2\right\}$$

New:

$$\lambda \approx \frac{1}{2} Re\left\{g_{LL}^V \cdot g_{LR}^{V*}\right\}$$

In left-right symmetric models with mixing angle ζ:

$$\lambda \approx \frac{1}{2}\zeta$$

Contribution from	$\frac{\Delta G_\mathsf{F}}{G_\mathsf{F}}$ $[10^{-6}]$	
	$\mu^+ \to \overline{\nu}_\mu e^+ \nu_e$	$\tau^+ \to \overline{\nu}_\tau \mu^+ \nu_\mu$
Δm_W	0.0	1
$\Delta m_{\mu,\tau}$	0.2	421
$\Delta \tau$	9.1	2 070
$\Delta(\lambda m_{\overline{\nu}})$	70.0	22 500
$\Delta \eta$	193.0	6 500
$\Delta \Gamma_{\tau \to \mu}$	-	100 000

5. Experimental method

Measure the complete polarization vector of the decay positrons:

$$\boldsymbol{P}_{e^+} = \begin{pmatrix} P_{\mathsf{T}_1} \\ P_{\mathsf{T}_2} \\ P_{\mathsf{L}} \end{pmatrix} \equiv \begin{pmatrix} P_{\mathsf{T}} \cdot \cos\varphi \\ P_{\mathsf{T}} \cdot \sin\varphi \\ P_{\mathsf{L}} \end{pmatrix}$$

with 3 simultaneous and independent measurements:

Observable	Method
P_{T}	Time dependence of annihilation
φ	Remnant μSR effect
P_{L}	Spatial dependence of annihilation

6. Experimental setup

6.1 Highly polarized μ^+ beam at μE1 area of PSI: (91%)

6.2 Muon stop rate in Be target: $(20 - 80) \times 10^6$ s^{-1}

6.3 Precession in homogeneous $\boldsymbol{B}$ field; precession frequency = cyclotron frequency (50.8 MHz)

6.4 Burst width 3.9 ns (FWHM)

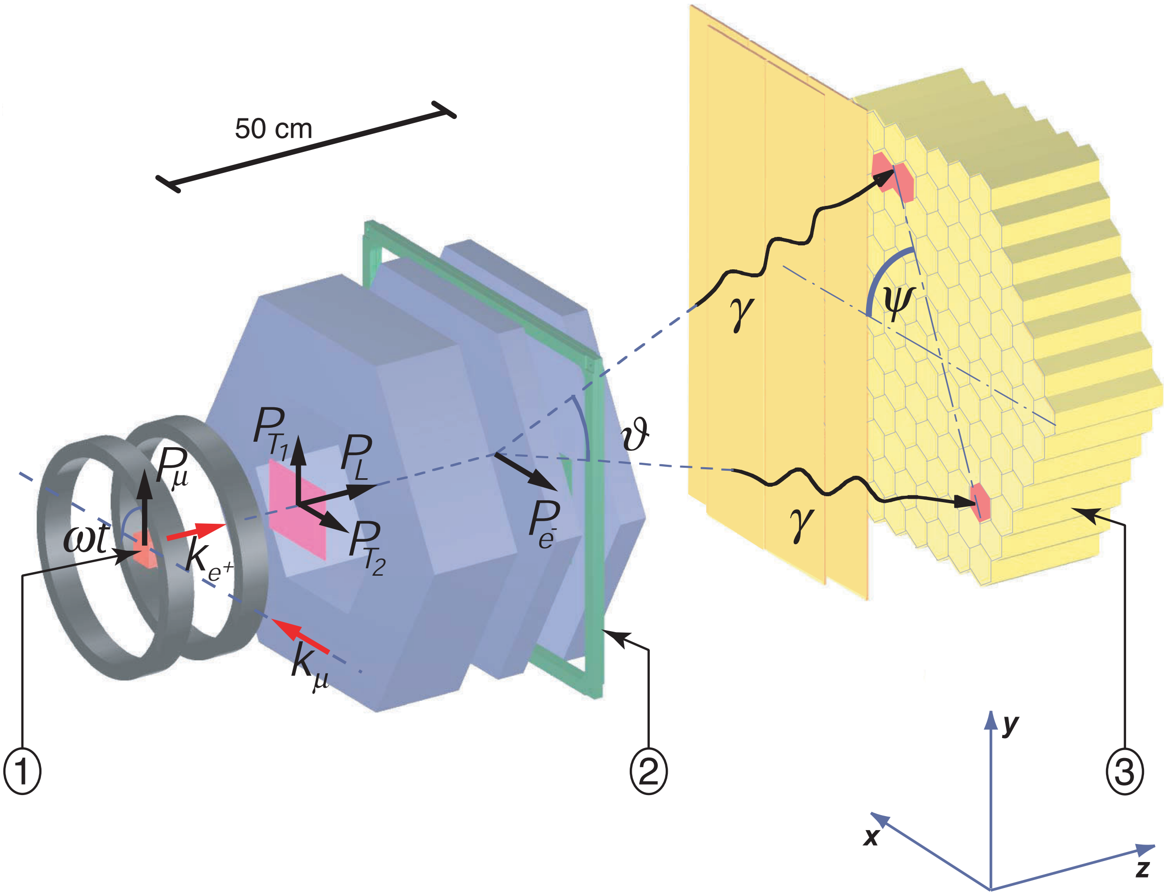
$\Longrightarrow$ 80% muon polarization in Be stop target

6.5 Positron tracking with drift chambers

6.6 Annihilation with polarized e^-

6.7 Detection of annihilation quanta with 127 BGO crystals

Setup of the Experiment and Principle of Measurement



① : Beryllium stop target within spin precession magnet

② : magnetized Vacoflux foil within iron return yoke

③ : calorimeter consisting of 127 BGO crystals

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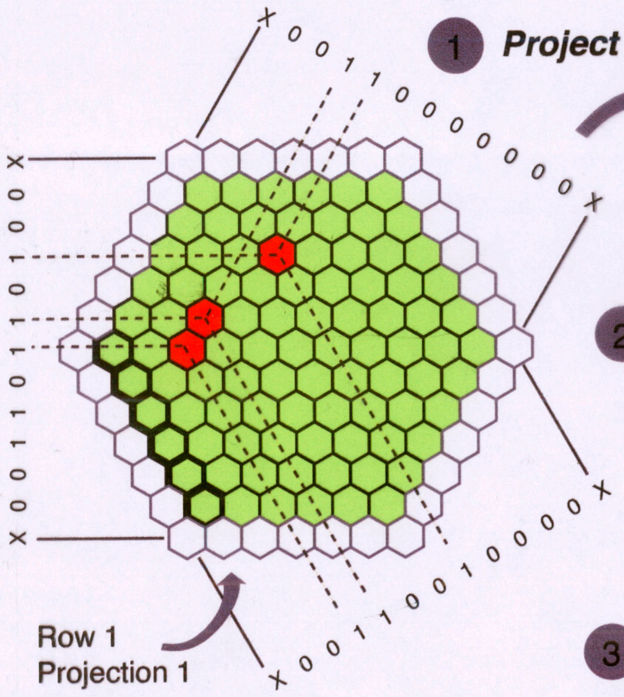
Triggering on Two Photons at a minimal Distance: The Cluster Recognition Unit

How does it work?

Kinematics require a minimal cluster distance

$$\cos\vartheta = 1 - m_e \frac{4}{E_{e^+}} \qquad d = 2z\tan\frac{\vartheta}{2}$$

$$d_{min} = d(E_{e^+} = 50 MeV) \approx 16\, cm$$



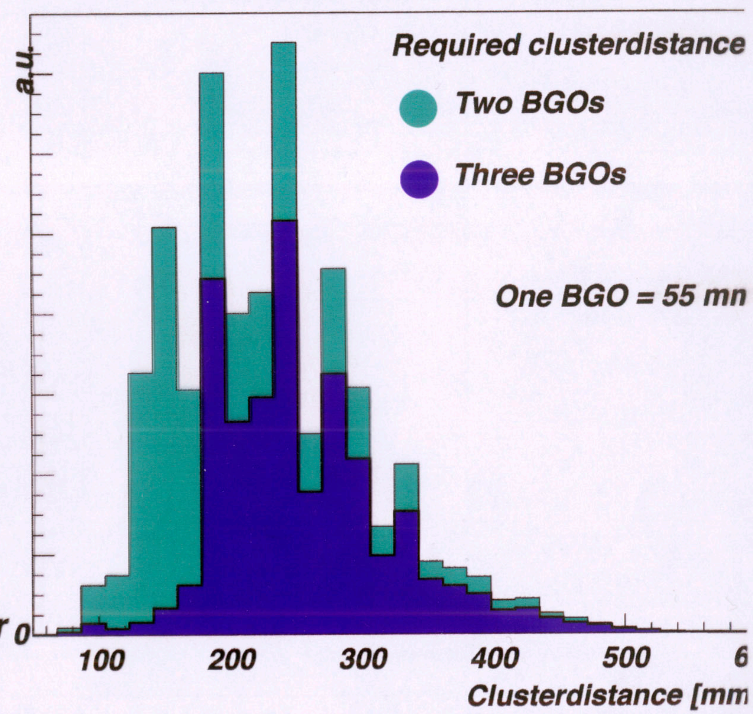
1. ***Project along the axes of symmetry***

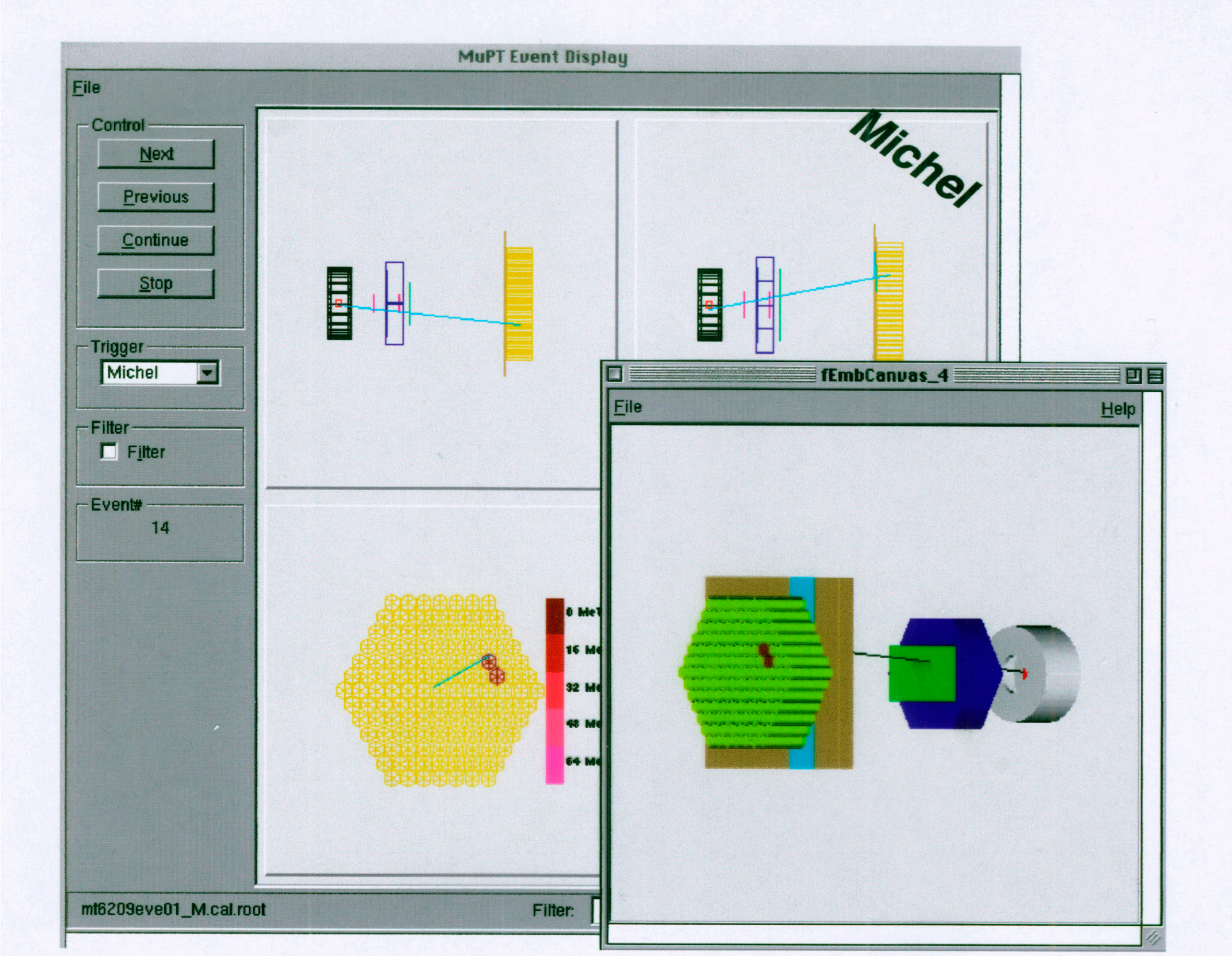
2. ***count groups of connected `1` and require at least two `0` in between***

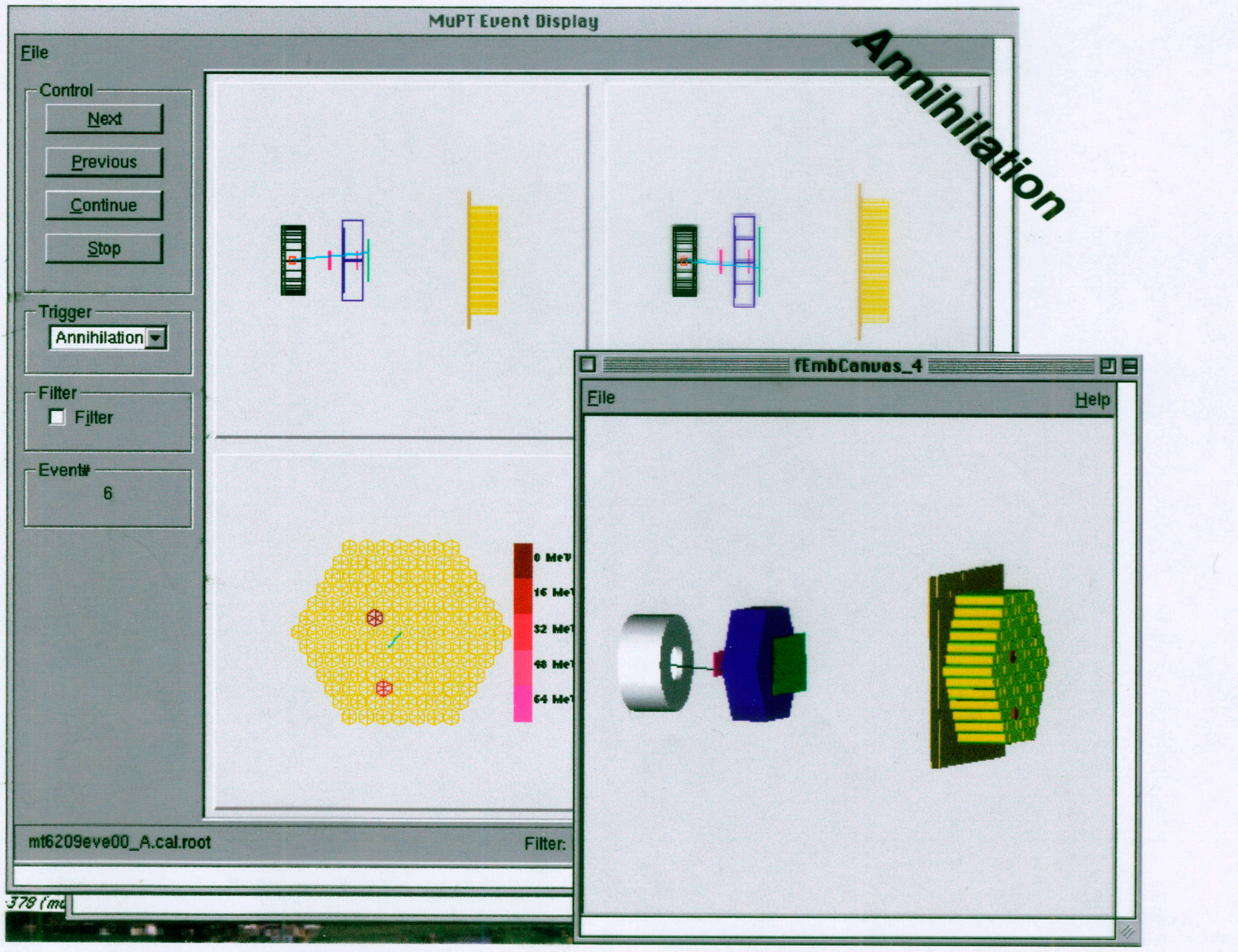
3. ***If #clusters =2 and distance ≥2 in any of the projections: Trigger***

FPGA aproach allows redefining trigger conditions `on the fly`

Distance between two clusters

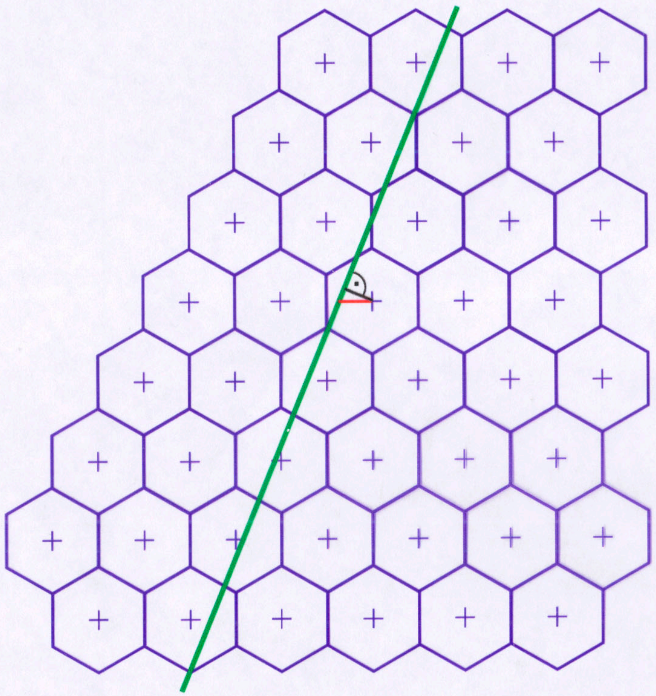



MuPT Event Display
File
Control
Next
Previous
Continue
Stop
Trigger
Michel
Filter
Filter
Event#
14
Michel
fEmbCanvas_4
File
Help
mt6209eve01_M.cal.root
Filter:

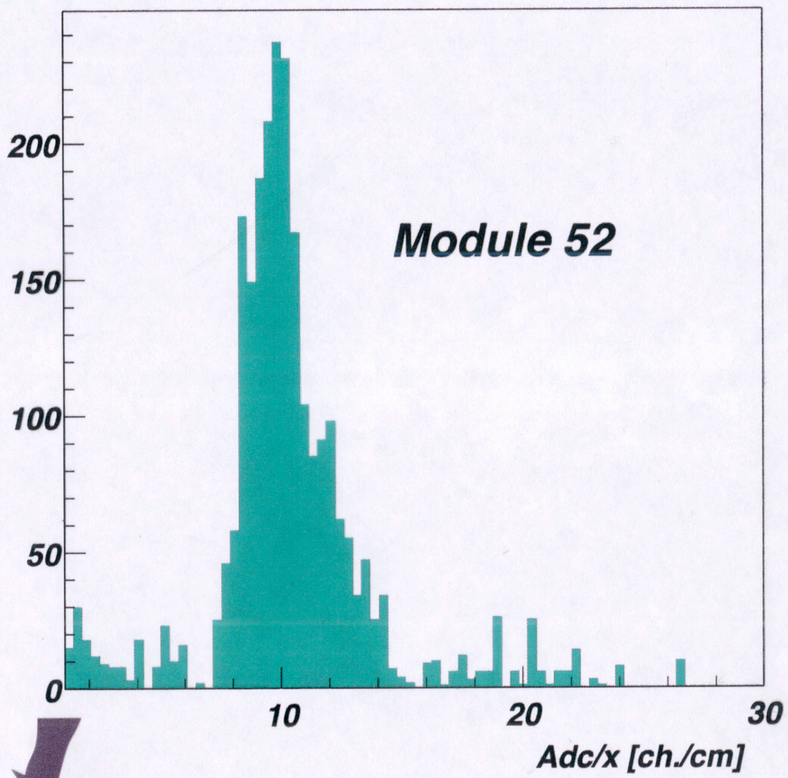

MuPT Event Display
File
Control
Next
Previous
Continue
Stop
Trigger
Annihilation
Filter
Filter
Event#
6
Annihilation
fEmbCanvas_4
File
Help
mt6209eve00_A.cal.root
Filter:

Data is Calibrated with Cosmic Muons

Reconstructing the cosmic tracks gives the tracklength in BGOs



Histogram Adc/x for cosmics



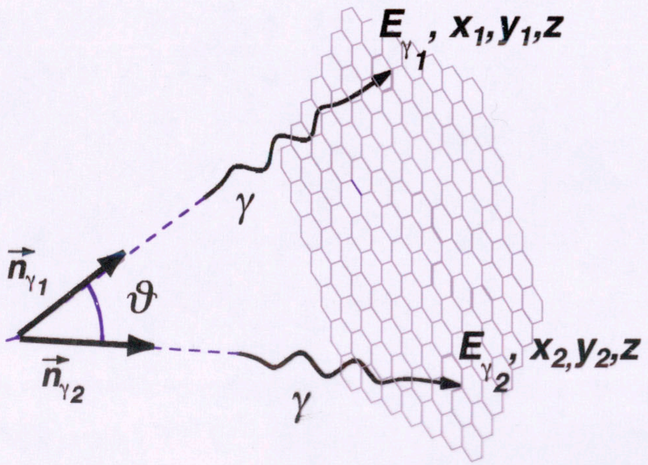
Monte Carlo

$$\frac{1}{E_i/x_i} \times \frac{ADC_i}{x_i} = \frac{ADC_i}{E_i} = c_i$$

Calibration constant for BGO number i

Cut on the Kinematics to Extract the 'Good' Events

Calculate ϑ in two different ways:



Energy:

$$\cos\vartheta = 1 - m_e \frac{E_{\gamma_1} + E_{\gamma_1}}{E_{\gamma_1} \cdot E_{\gamma_1}}$$

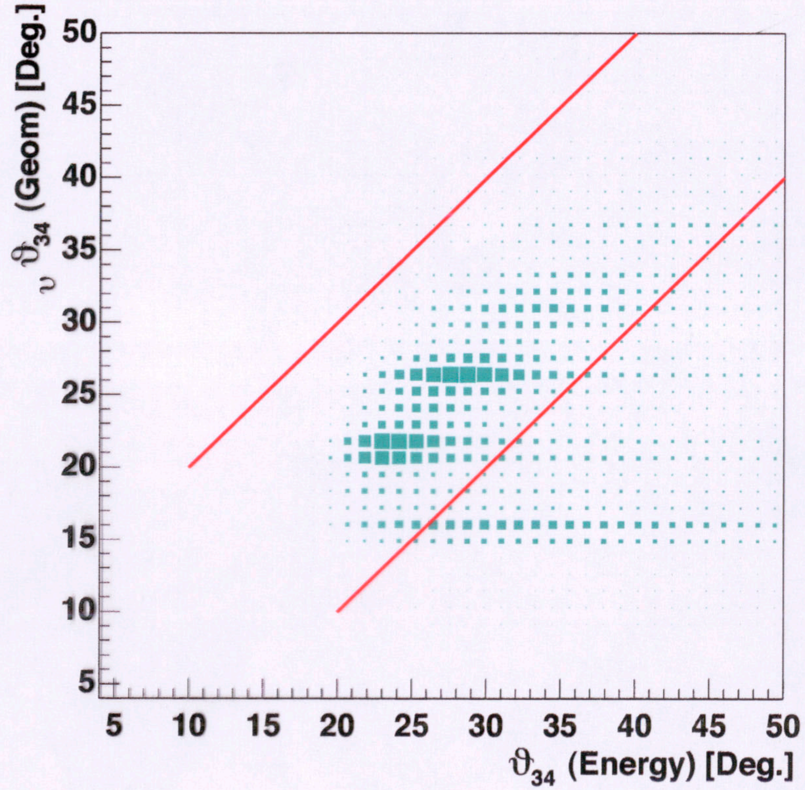
Geometry

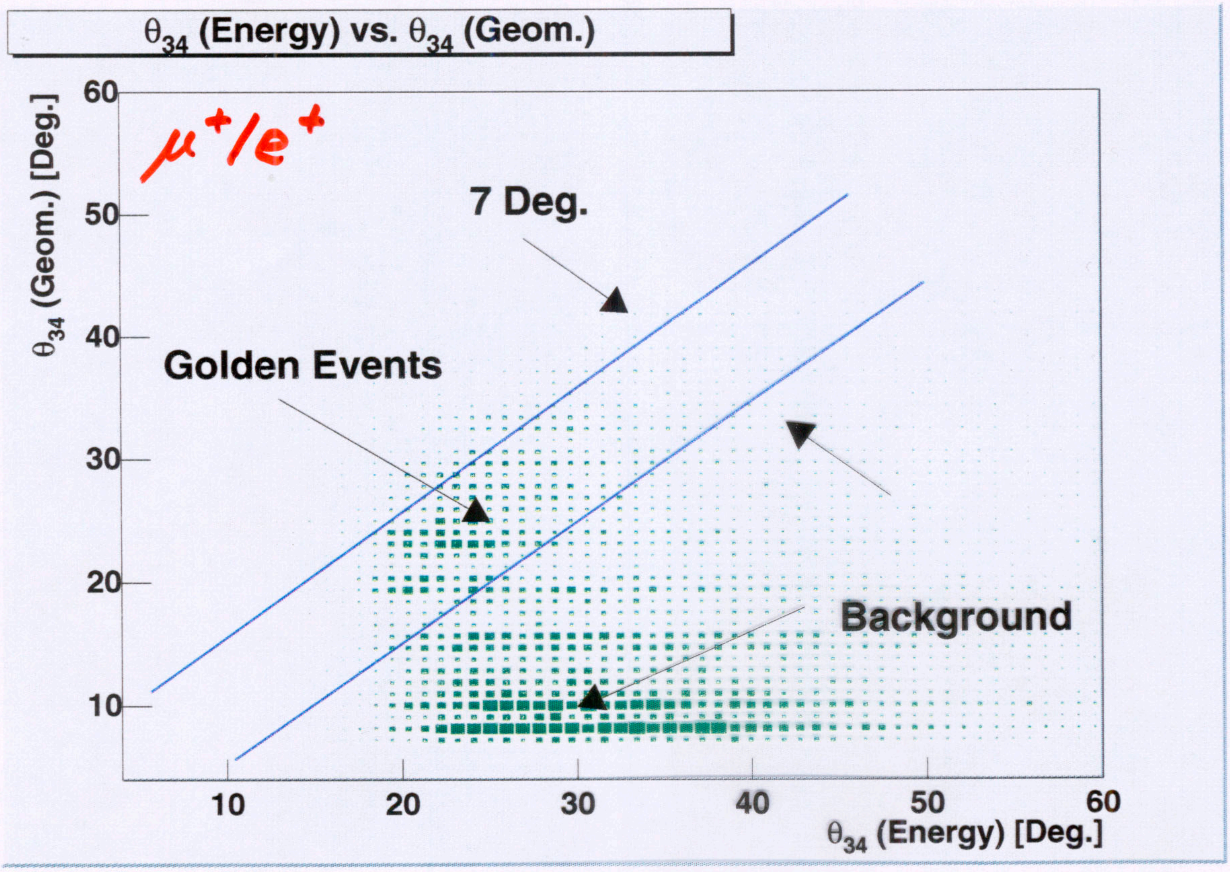
$$\cos\vartheta = \vec{n}_{\gamma_1} \cdot \vec{n}_{\gamma_2}$$

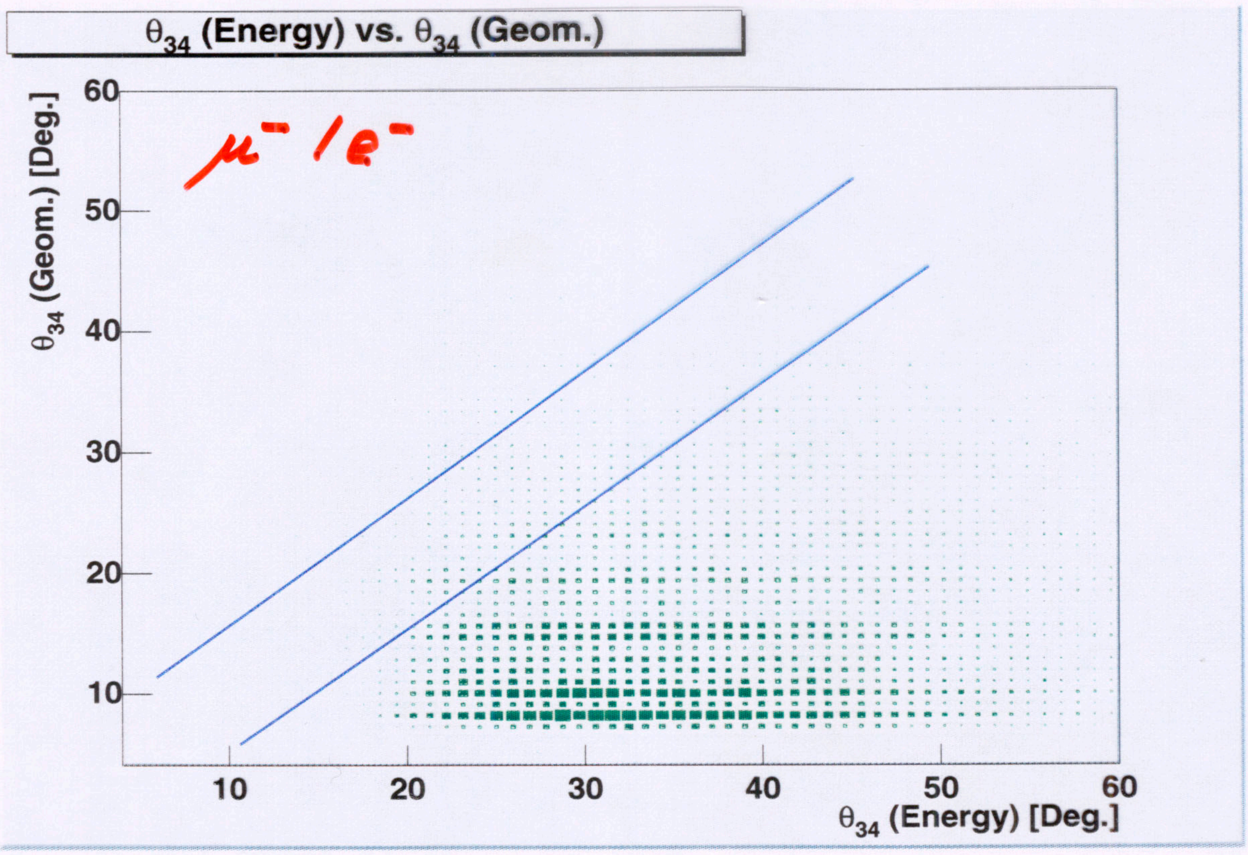
$$\vartheta^{Geom} = \vartheta^{Energy}$$

for 'good' annihilations

Sample from the last run

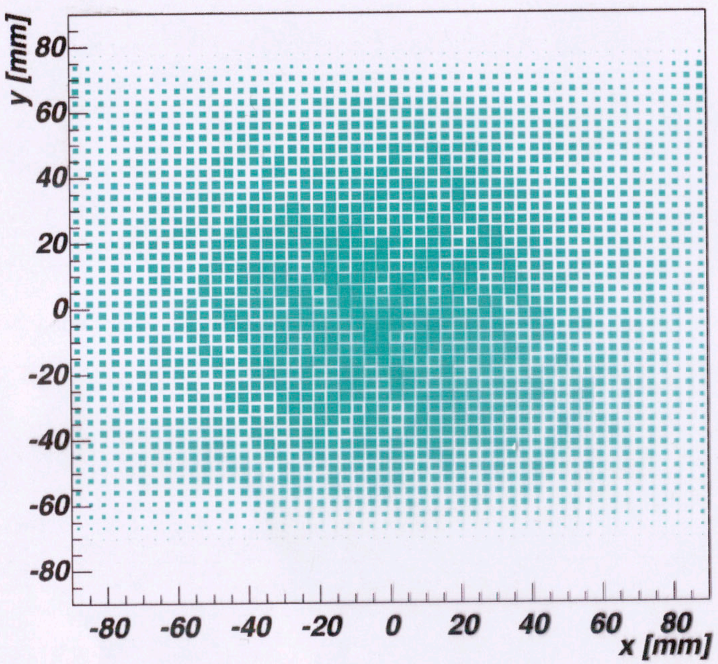



θ34 (Energy) vs. θ34 (Geom.)
μ+/e+
7 Deg.
Golden Events
Background
θ34 (Geom.) [Deg.]
θ34 (Energy) [Deg.]
10
20
30
40
50
60


θ34 (Energy) vs. θ34 (Geom.)
μ−/e−
θ34 (Geom.) [Deg.]
θ34 (Energy) [Deg.]
10
20
30
40
50
60

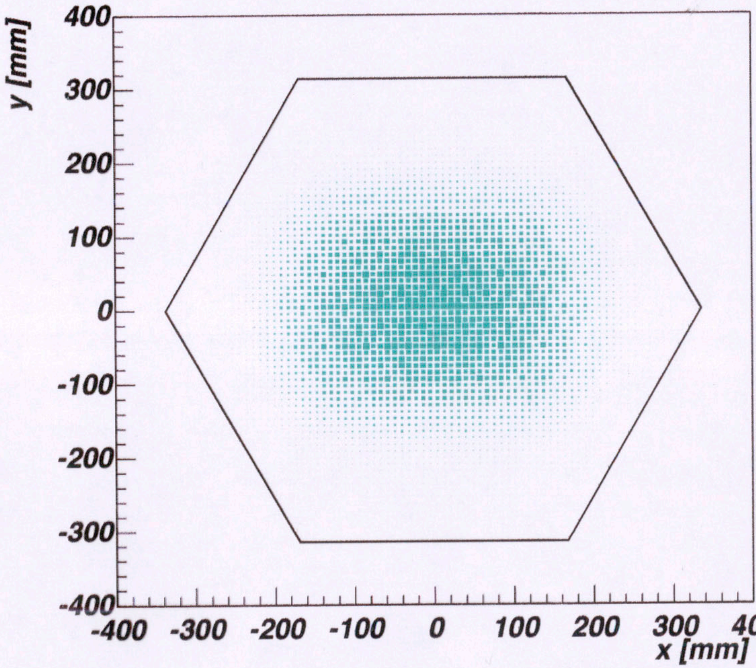
Where do `good` annihilations

come from,



reconstructed position
of annihilations on the foil

and where do they go?

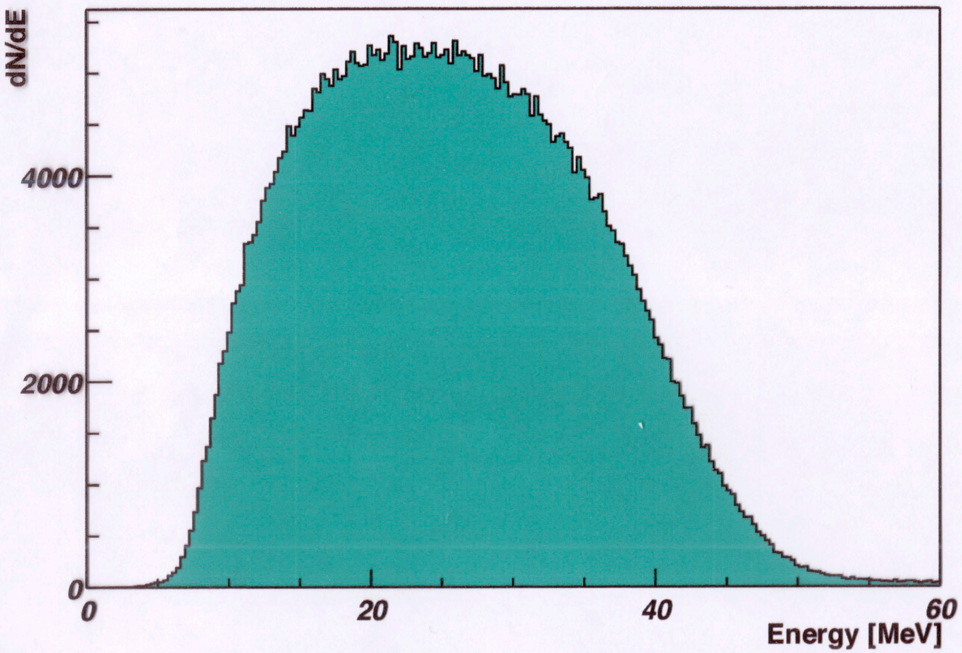


center of energy on the BGO-wall

Analysis, Step Two: From Raw Data to `Good` Events

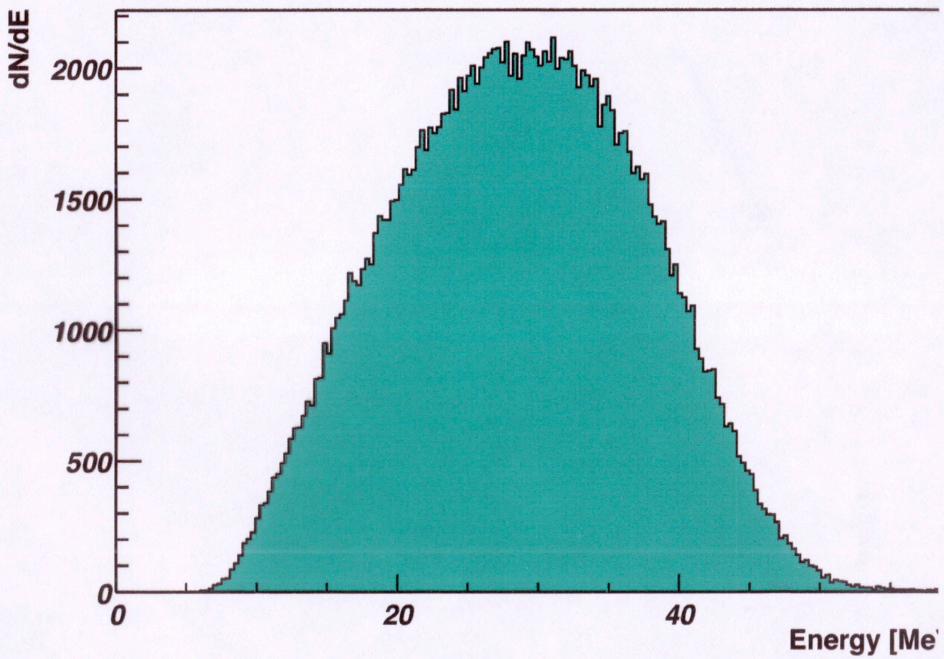
Energy ($E_{tot} = E_{\gamma 1} + E_{\gamma 2}$) spectra of annihilation events

After reconstruction (≈50 % Eff.)



charged track reconstructed, exactly two clusters in the BGO.

After selection (≈34 % Eff.)



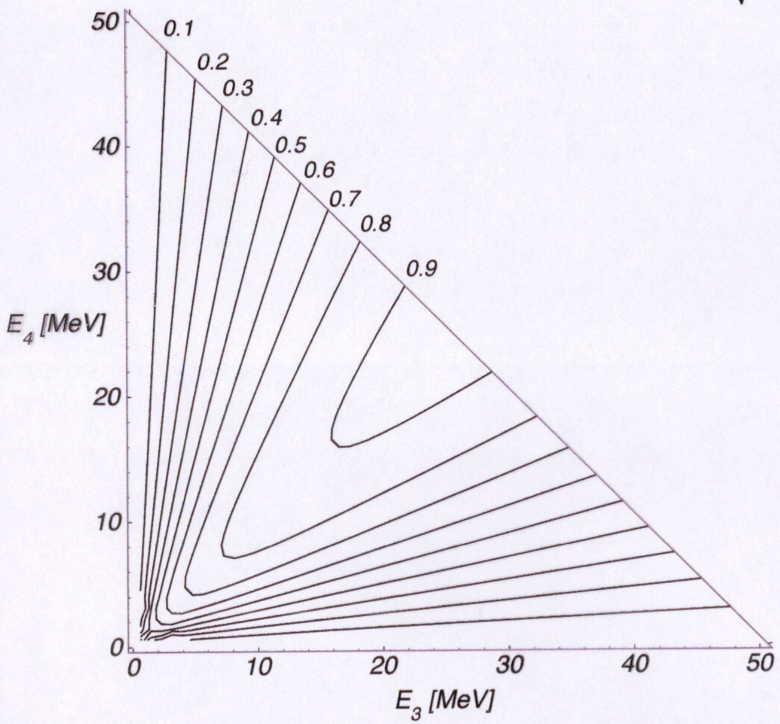
event kinematics must be consistent with annihilation hypothesis.

After all cuts ≈17% `good` annihilation events remain.

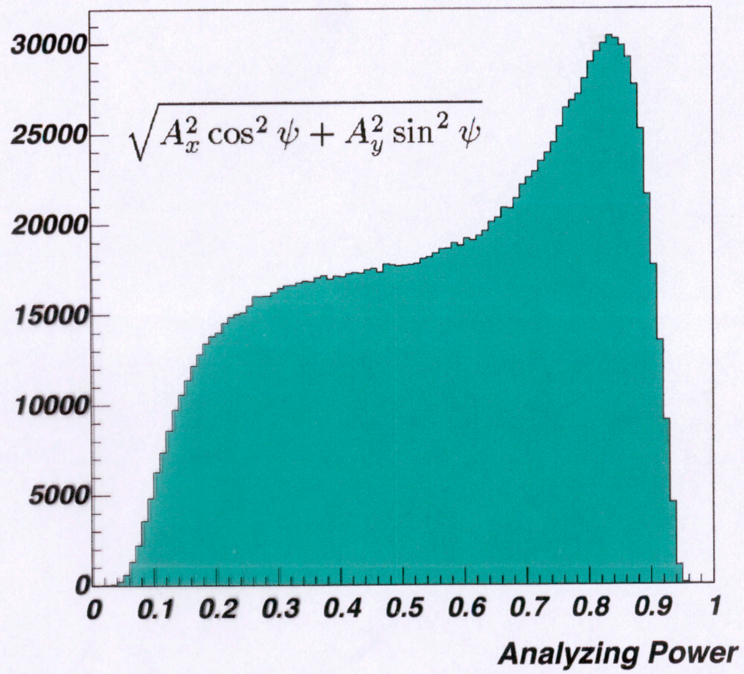
Theoretical and Experimental Analyzing Power

The analyzing power is the amplitude of the expected oszillation

$$\mathcal{A} \;=\; S \cdot \sqrt{P_1^2 + P_2^2} \cdot \sqrt{A_x^2 \cos^2 \psi + A_y^2 \sin^2 \psi}$$



Theoretical analyzing power,
$\Psi = 90^o$ $P_{e^-} = 100\%$, $|P_T| = 1$



Analyzing Power of `good` annihilation events.
A_x and A_y are functions of the photon energies

8. Data analysis

$$R(t) = F_{\mathrm{TDC}}(t) \cdot F_{\mu}(t) \cdot F_{\mu\mathrm{SR}}(P_{\mu}, E_1, \alpha, \chi, t) \cdot F_{\gamma\gamma}(E_3, E_4, \boldsymbol{P}, P_{e^-}, \alpha, \chi, \psi, t)$$

Quantity	Symbol
μ^+ polarization	P_μ
e^+ energy e^+ direction	E_1 (α, χ)
e^+ polarization	$\boldsymbol{P} = (P_x, P_y, P_z)$
e^- polarization	P_{e^-}
γ energies analysing powers	E_3, E_4 A_x, A_y, A_z
azimuthal angle of BGO pair	ψ

$$F_{\mu\mathrm{SR}}(P_\mu, E_1, \alpha, \chi, t) = 1 + P_\mu A(E_1) \sin\chi \cos(\omega t - \alpha - \delta_0)$$

$$\begin{aligned} F_{\gamma\gamma}&(E_3, E_4, \boldsymbol{P}, P_{e^-}, \alpha, \chi, \psi, t) \\ &= 1 + P_{e^-} \cdot P_\mu \cdot \cos(\omega t - \delta_0)\,[P_x \cdot G + P_y \cdot H] \\ &\quad + P_{e^-} \cdot P_\mu \cdot \sin(\omega t - \delta_0)\,[P_x \cdot H - P_y \cdot G] \\ &\quad + P_{e^-} \cdot P_z \cdot A_z \cos\alpha \sin\chi \end{aligned}$$

$$G \equiv A_x \cos^2\psi + A_y \sin^2\psi$$

$$H \equiv (A_x - A_y) \sin\psi \cos\psi$$

How can we extract the e^+ transverse polarization (P_x, P_y) from the data?

Harmonic oscillation:

$$\begin{aligned} F(t) &= 1 + a \cos\omega t + b \sin\omega t \\ &= 1 + A_{\mathrm{F}} \cos(\omega t - \varphi) \end{aligned}$$

Solution: Fourier analysis; neglect multiples of ω.

#	Effect	$A_F \times 10^3$
1	Residual (Beam micro-structure & muon decay & TDC diff. nonlinearity)	8.3
2	μSR (decay asymmetry)	210.0
3	ΔP_T	0.3

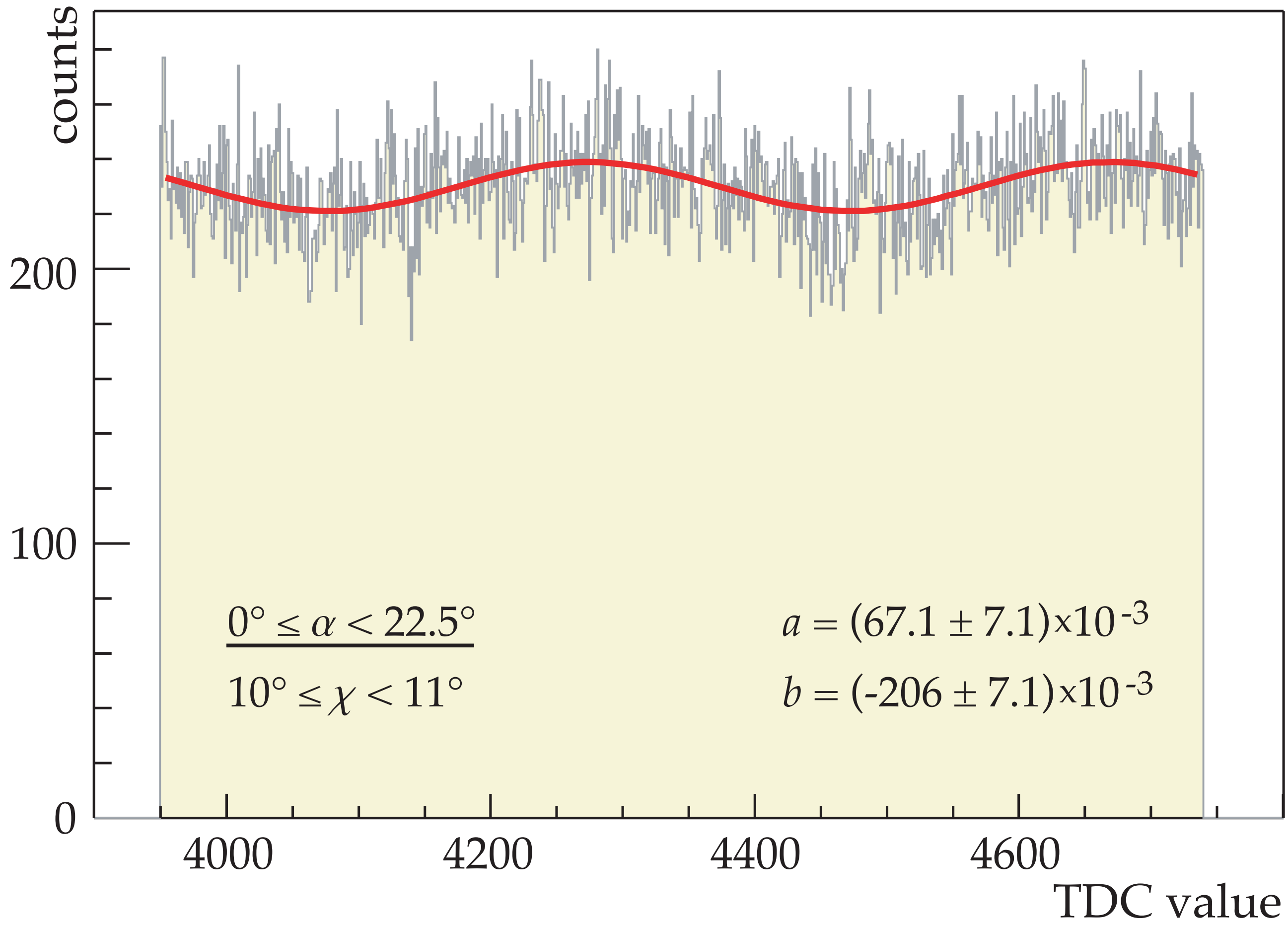
Make use of the various inherent symmetries:

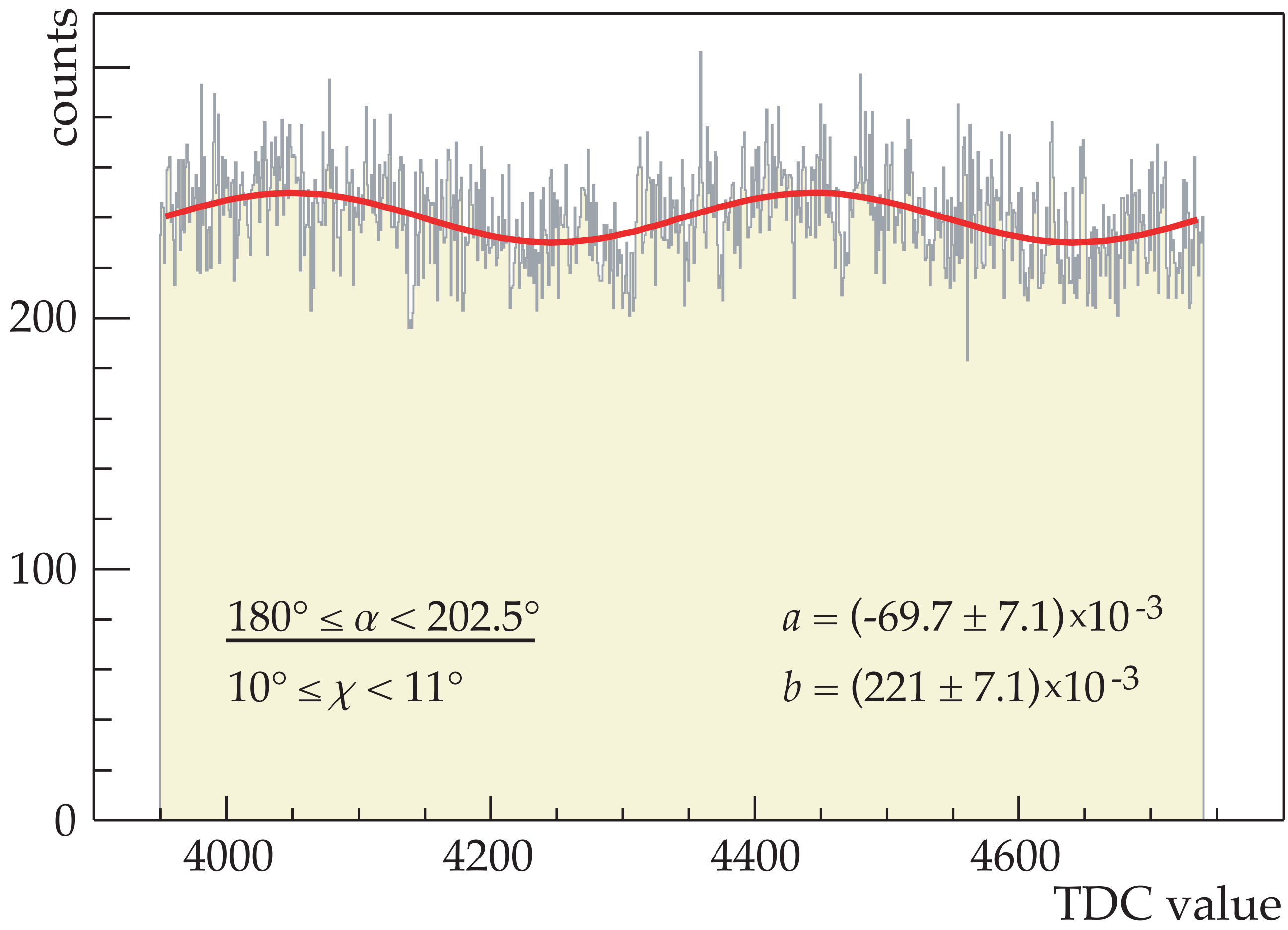
1: Integrate over time, sum over P_{e^-}, integrate over positron direction (α, χ):

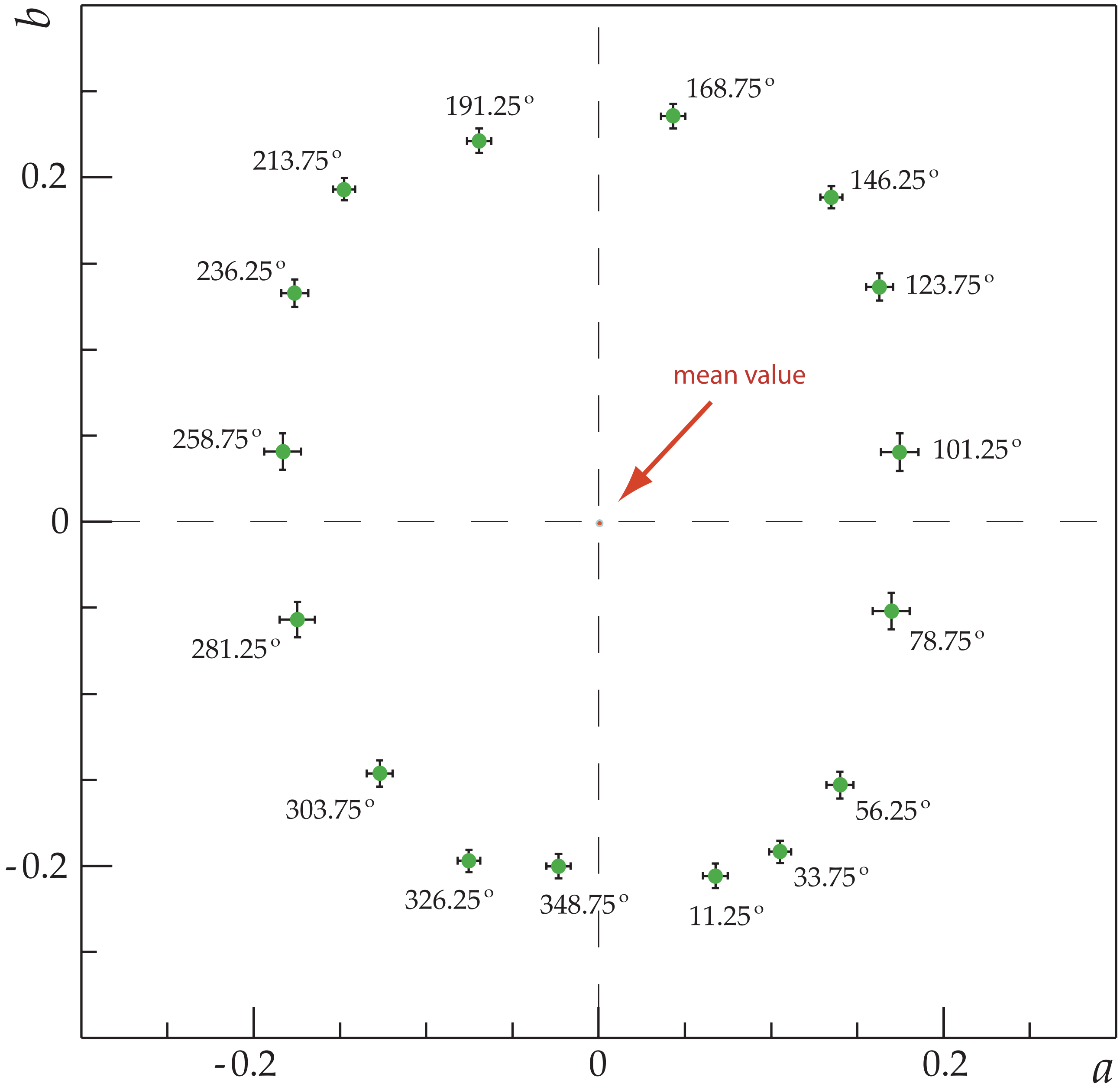
$$\Rightarrow a_{\text{res}}, b_{\text{res}}$$

2: Sum over P_{e^-}, determine as a function of the positron direction (α, χ), subtract $a_{\text{res}}, b_{\text{res}}$ and finally, divide by $P_\mu \sin\chi$:

$$\Rightarrow a_{\mu\text{SR}}(\alpha), b_{\mu\text{SR}}(\alpha), \text{Phase } \delta_0$$


counts
200
100
0
4000
4200
4400
4600
TDC value
0° ≤ α < 22.5°
10° ≤ χ < 11°
a = (67.1 ± 7.1)x10^-3
b = (-206 ± 7.1)x10^-3


counts
200
100
0
4000
4200
4400
4600
TDC value
180° ≤ α < 202.5°
10° ≤ χ < 11°
a = (-69.7 ± 7.1)x10^-3
b = (221 ± 7.1)x10^-3



Fourier coefficients $a_{\mu\mathrm{SR}}(\alpha), b_{\mu\mathrm{SR}}(\alpha)$

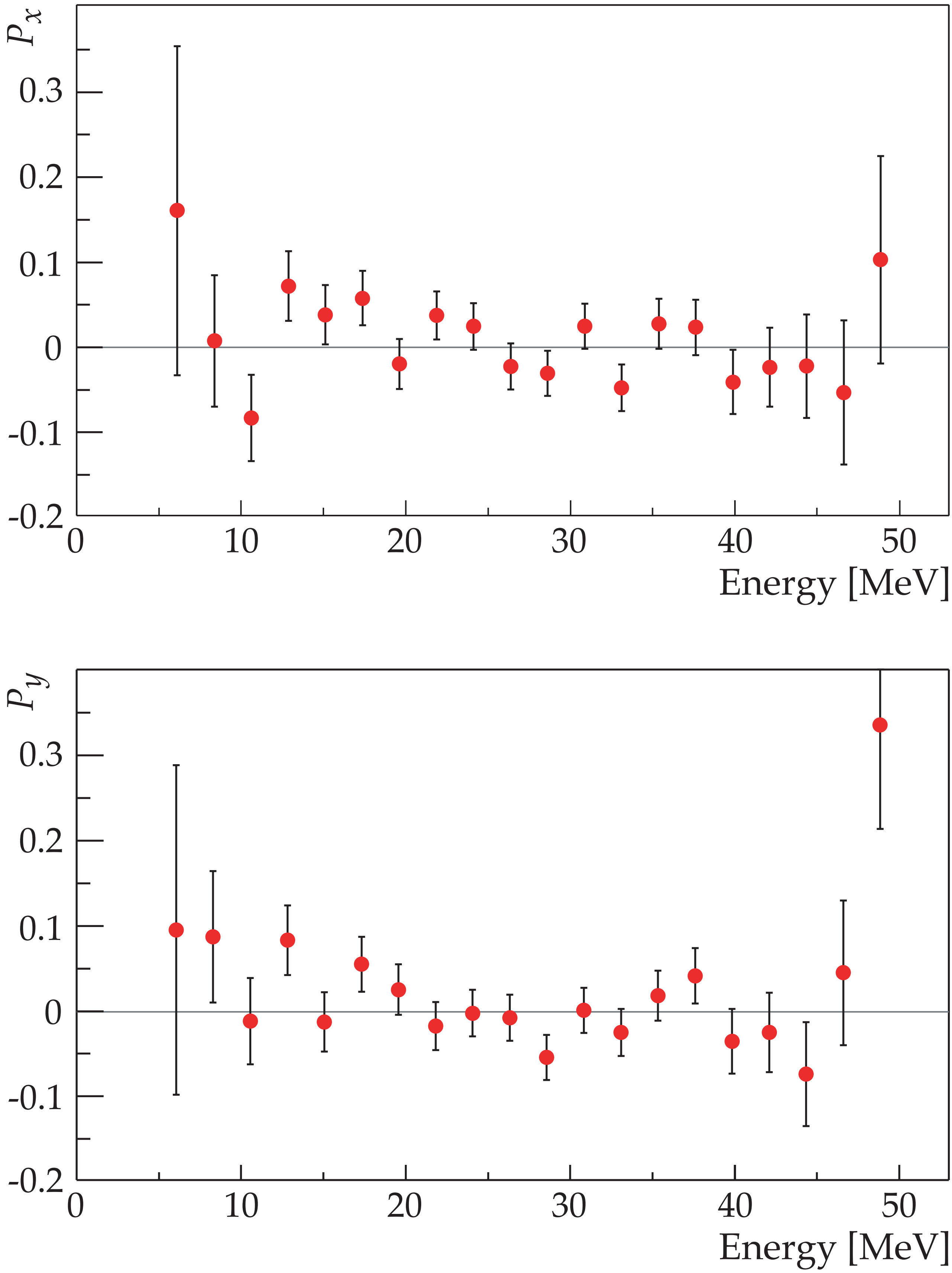
Determine $P_\mu(t)$!

3: Integrate over positron direction (α, χ), subtract coefficients for $P_{e^-} = -1$ from coefficients for $P_{e^-} = +1$.

$\Rightarrow (P_x, P_y)$

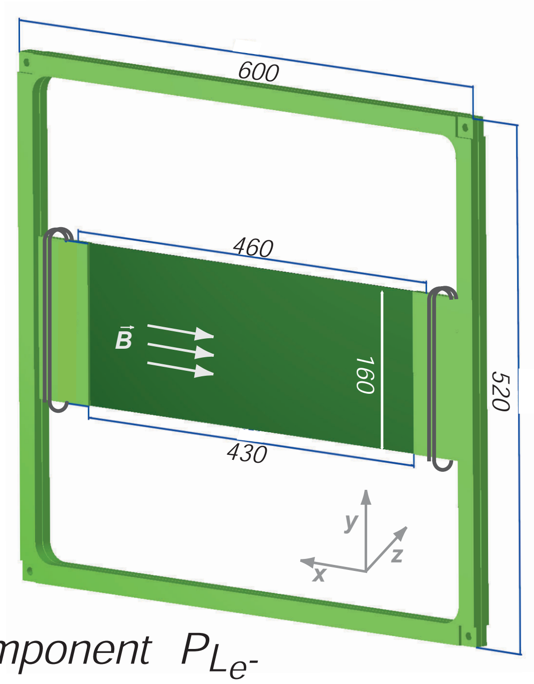
Transverse e^+ polarization components

at the moment of annihilation



Measurement of the Longitudinal Polarization

using information about position
on magnetized Vacoflux foil
(determined by tracks reconstructed
from drift-chamber data)
where annihilations take place

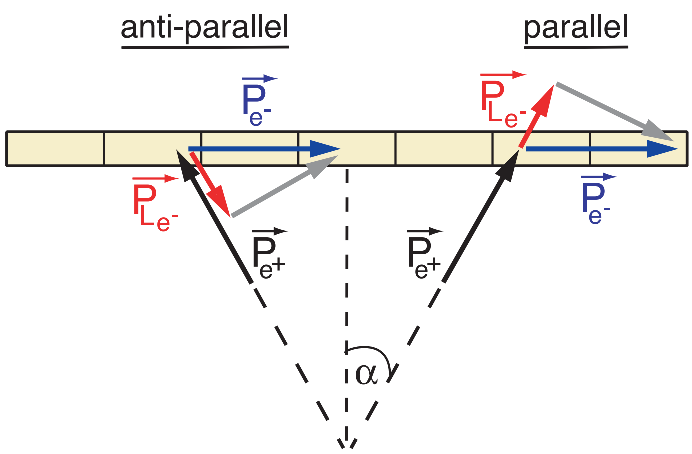


area on foil taken into account: 140^2 mm^2

area divided into rectangular bins (ij),
17 bins in x- and y-direction, respectively

Tracks that do not hit the center of the foil 'see' a longitudinal component $P_{L_{e^-}}$ of the polarization of the electrons in the foil.

This $P_{L_{e^-}}$ can either be parallel or anti-parallel to the positron polarization :



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Longitudinal Polarization P_L of the Positrons

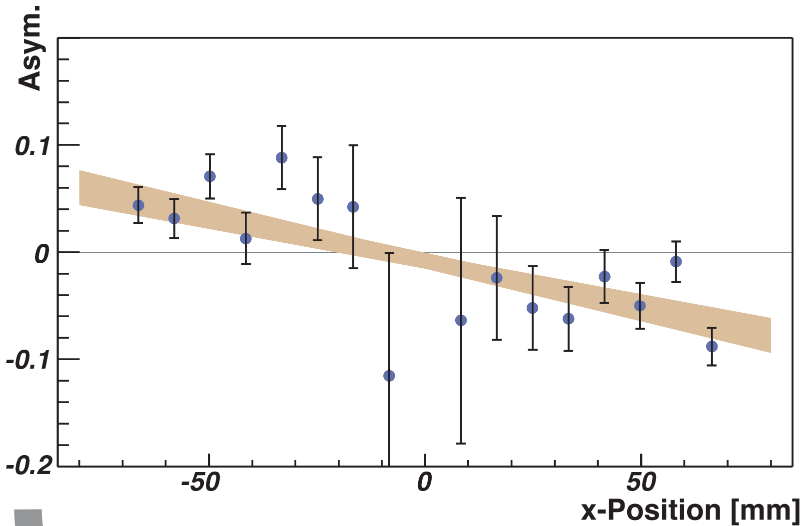
annihilation cross section depends on relative orientations of spins; it is larger if both spins are anti-parallel

Asymmetry: $$A_{ij} = \frac{\frac{n_{ij}^-}{N^-} - \frac{n_{ij}^+}{N^+}}{\frac{n_{ij}^-}{N^-} + \frac{n_{ij}^+}{N^+}}$$

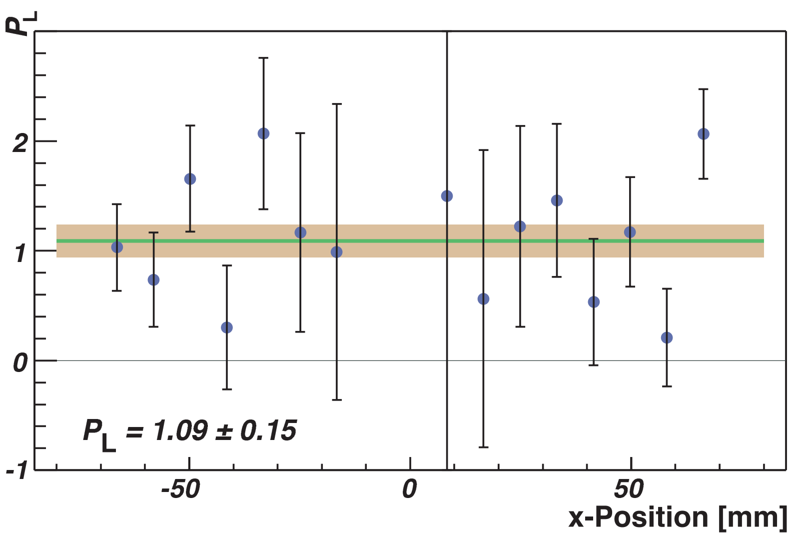
where n_{ij}^+ : number of annihilations in bin *ij* for positive foil polarization

N^+ : total number of annihilations for positive polarization

n_{ij}^-, N^-: same for negative polarization



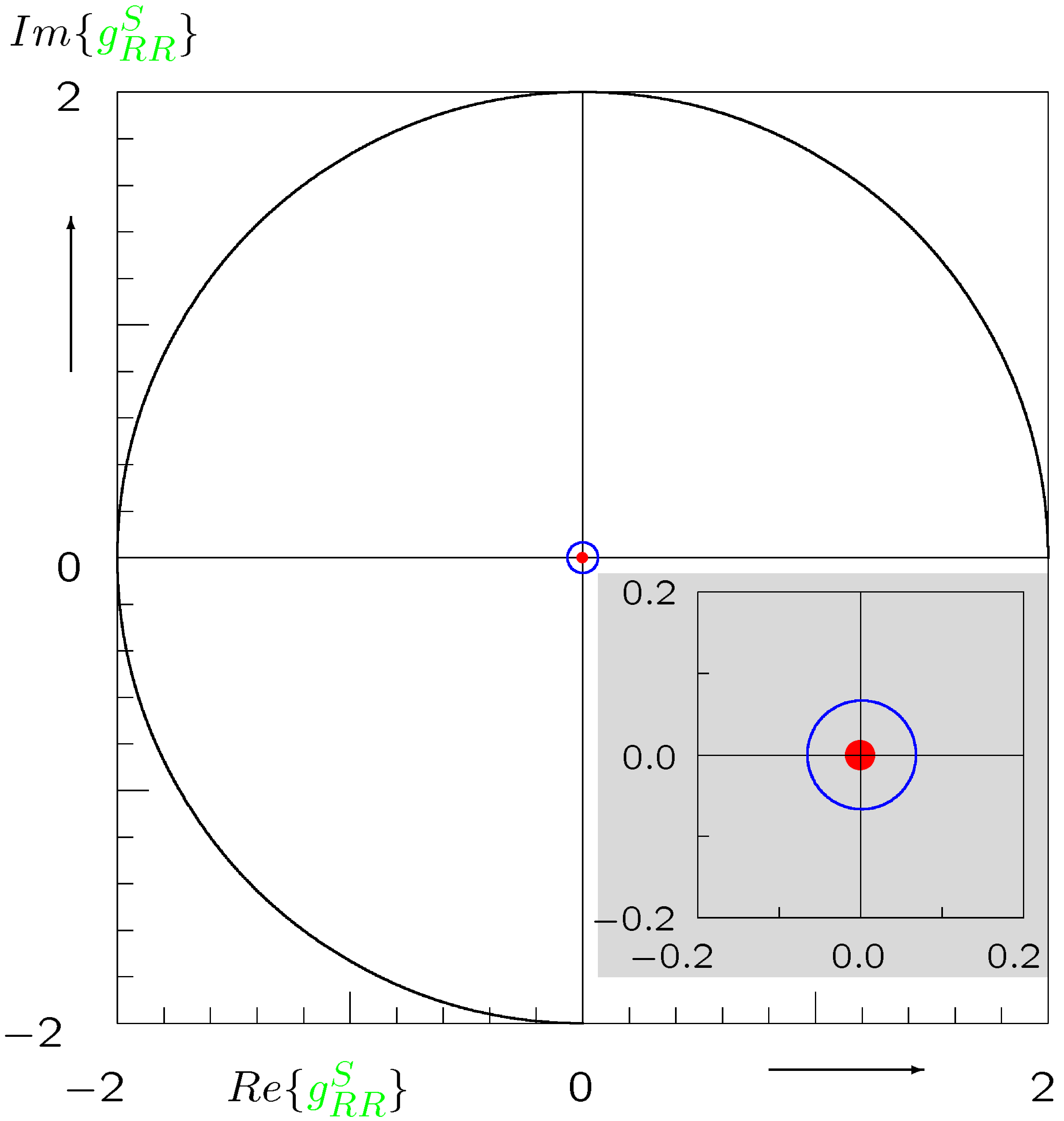
- angle α
- elektron polarization in foil (P_{e-} = 7.2 %)
- analysing power of 0.79
- background factor of 0.75 (backgr. ratio 25 %, mainly due to bremsstrahlung)



8. Preliminary Results

All results are compatible with the standard model. Analysis is in progress. The experimental errors are given below:

	General analysis	V - A + g^S_{RR}
$10^3 \times \Delta\langle P_{\mathrm{T}_1}(90°)\rangle_E$	14	14
$10^3 \times \Delta\langle P_{\mathrm{T}_2}(90°)\rangle_E$	14	14
$10^3 \times \Delta\eta$	53	10
$10^3 \times \Delta\eta''$	75	10
$10^3 \times \alpha'/A$	31	-
$10^3 \times \Delta\beta'/A$	11	5
$10^3 \times \Delta$ Re g^S_{RR}	–	20
$10^3 \times \Delta$ Im g^S_{RR}	–	20
$10^3 \times \Delta\lvert g^S_{RR}\rvert$	–	20



Limits for scalar coupling g^S_{RR}.

Black (outer) circle: by definition.

Blue circle: previous measurement [1]

Inner red circle: this measurement.

Position of red circle: not yet determined.

9. Outlook

Improve precision of previous experiment [1] by almost one order in magnitude to:

$$\Delta\langle P_{T_1}(90^0)\rangle = 0.008$$
$$\Delta\langle P_{T_2}(90^0)\rangle = 0.008$$

Assuming $V - A$ and one additional coupling , this will reduce the limits for η and g^S_{RR} to

$$\Delta\eta = 0.006$$
$$\Delta Re\{g^S_{RR}\} = 0.011$$
$$\Delta Im\{g^S_{RR}\} = 0.011$$

[1] H. Burkard, F. Corriveau, J. Egger, W. Fetscher, H.-J. Gerber, K.F. Johnson, H. Kaspar, H-J. Mahler, M. Salzmann, F. Scheck

Phys. Lett. **160B** (1985) 343.